JPL D-13277, Rev. B

RISK/REQUIREMENTS TRADE-OFF GUIDELINES

FOR FASTER, 13 ETTER, CHEAPER MISSIONS

Prepared by the Reliability Engineering Office of the Office of Engineering and Mission Assurance

April, 1996

JPL

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

PREFACE

This document is a compendium of Risk/Requirements Tradeoff Guidelines for Faster, Better, Cheaper missions. It summarizes the reduced-cost approach for the design, verification, and validation of flight equipment for assuring mission success of microspacecraft.

The first edition (Rev. A) of the document contained guidelines for a subset of product assurance activities that have been deemed critical in a recent study to prioritize them. This second edition (Rev. B) of the document contains more product-assurance guidelines from the prioritized list. Additional guidelines, not included in this revised document, will be included in future revisions. These guidelines are self-optimized in the parameters to whose variance they are sensitive. in order for the entire product assurance program to be optimized, the guidelines need to be optimized with respect to each other. Optimization bet ween related disciplines (e.g. dynamic, thermal, analysis, etc.) will be made from existing guidelines in the next revisions. subsequent revisions will involve optimization across disciplines and for combined disciplines. This document is intended to assist projects in their re-engineering effort, thus the guidelines will be periodically revised and updated to reflect the changing needs of future missions.

DOCUMENT CHANGE LOG

REVISION	DATE	CHANGE DESCRIPTION	PREPARED BY
Rev. A	January 1996	First Release	Reliability Technology Group, 505 (Kin F. Man, Editor)
Rev. B	April 1996	Second Release	Reliability Technology Group, 505 (Kin F. Man, Editor)

ACKNOWLEDGMENTS

The work described in this document was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA), It was funded by NASA Code QT under the Research Technology Operation Plan (RTOP), UPN 623-63-03 and 323-71 -3C. We are grateful to Mr. Tom Gindorf, Manager of the Assurance Technology Program Office, for his initial involvement in starting up this task and his continuing support,

This task is under the leadership of Dr. Steven L. Cornford, Program Element Manager of Payload Assurance in the Assurance l'ethnology Program Office and Supervisor of the Reliability Technology Group in 505. This document is the product of the efforts of a number of personnel within the Reliability Engineering Office and other Offices within the Office of Engineering and Mission Assurance. Each guideline may be the work of one or more contributors. q'heir efforts are greatly appreciated. The following table lists the primary author of each guideline, to whom detailed technical questions should be directed.

Guideline	Primary Contributor
Rev. A	
1. Acoustic Noise Requirement	Jim Newell
2. Pyrotechnic shock Requirement	Jim Newell
3. Radiation Design Margin Requirement	Michael Cherng
4, Minimum Operating Time Requirement	Milena Krasich
5. System-Level Fault Tree	John Koch
6. Electronic Parts Stress Analysis	John Koch
7. Unit Level Temperature Design Requirement	Tim Larson
Rev. B Additions	
8. Unit Level Thermal Test Requirement	Mark Gibbel
9. Electronics Parts Destructive Physical Analysis	Stephen James
10. Quality Assurance Site Survey Requirement	Diane Sipes-Cwik
11. Electrostatic Discharge Control Program Requirement	Kirk Olsen

Many of the authors have reviewed the guidelines. Valuable review comments were also provided by Phil Barela, Steve Cornford, Chuck Gonzalez, Richard Kemski, and Kin Man. In addition, Perry Danesh, Ken Erickson, Lynn Gresham, Jim Moldenhauer, Guy Spitale, anti Al Whittlesey have taken part in discussion meetings to generate valuable ideas for this task.

The editor is responsible for any remaining errors and welcomes comments and suggestions for improvement to its usefulness. Questions or comments should be directed to Dr. Kin F. Man, at (818) 393-0255.

CONTENTS

INTRODUCTION

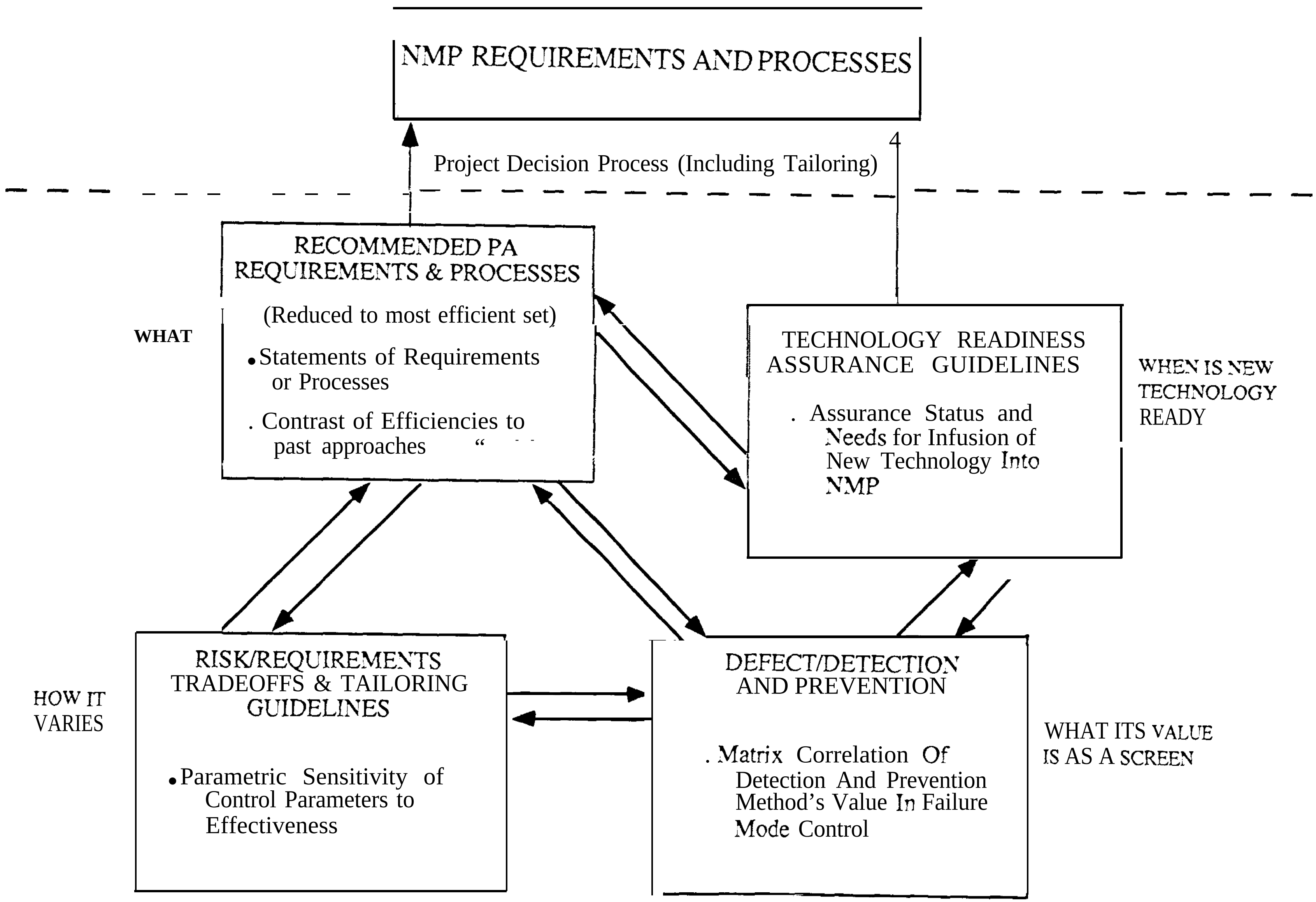
As the trend towards Faster, Better, Cheaper missions accelerates, it presents managers and project personnel with additional challenges of devising streamlined guidelines for implementing this new way of doing business. Thus, there is a renewed emphasis on tradeoffs between requirements and risk to reduce cost, while still improving quality, reliability, cost, and schedule. The risk/requirements tradeoff guidelines contained in this document are intended to assist projects in this endeavor. The objectives of these guidelines can be summarized generically as: to 1) demonstrate operation in a flight-like environment; 2) validate design; 3) demonstrate robustness; 4) detect workmanship flaws; and 5) demonstrate reliability. Each guideline addresses one or more of these objectives. The definition of these objectives, as used in the context of our task, are defined in greater detail below:

1. Demonstrate operation in a flight-like environment – demonstrate hardware operation to design levels in a flight-like environment in which several operational parameters may interact synergistically with each other and with the test environment.
2. Validate design --- demonstrate the ability of the electrical and/or mechanical hardware design to function within specifications in various operational modes (on/off cycles, start-up performance, deployment times, end-of-life conditions, etc.) and environments.
3. Demonstrate robustness -- demonstrate the ability of a unit to operate at levels beyond the expected flight/use environment, in order to quantify the various margins within a design. Testing to the limits of performance should not physically break or cause irreversible degradation or damage. Robustness demonstration typically involves electrical, mechanical, and thermal margins (e.g. sensitivity to voltage, clock frequencies, packaging, design performance, thermal degradation, structural integrity, etc.).
4. Detect workmanship flaws -- detect workmanship flaws that can cause time-dependent degradation to electrical and mechanical hardware, as well as non-time dependent failures. Workmanship flaws can result both from process variations in assembly, integration, and those that escaped from lower-level manufacturing operations,
5. Demonstrate reliability — demonstrate the ability of the flight hardware to operate the required functions under specified conditions for a stated period of time. Sufficient operating time (dwell and cycle) is accumulated through testing to eliminate "infant-mortality" defects and to provide a measure of the expected failure rate.

Each guideline focuses on a PACT (Prevention, Analysis, Control or Test) typically used to screen for specific potential failure. modes. A list of predominant failure modes relevant to each guideline is also generated. In some cases they are supported by results of searches from ground test and in-flight problem/failure databases for J}'], and GSFC flight missions. The significance of categories of failure modes to the achievement of overall mission success is addressed in terms of performance tradeoffs within the PACTS. Cost drivers in the performance of these specific PACTs are identified for potential tradeoff studies. Parametric tradeoffs that would be cost effective are indicated. In addition, effective substitutes for specific PACTS are identified.

These guidelines are the evolving product of the Risk/Requirements Tradeoff task. This task is part of a suite of four tasks in the New Millennium Mission Assurance Project Applications RTOP, sponsored by the]'ayloads/Aeronautics Division (QT) of the office of Safety and Mission Assurance (Code Q) at NASA. This suite of tasks are designed to function synergistically to enable the emerging needs of microspacecraft (μ-S/C) and to remove the roadblocks for achieving their goals (Figure 1), The first of the four tasks, the Recommended Product Assurance Requirements and Processes task, determines criteria for a minimum set of product assurance requirements to ensure mission success. It recommends a Set of specific reliability, environmental, parts, and quality requirements for μ-S/C applications. For each of the issues identified in the first task, the second task, in the form of tradeoff and tailoring guidelines, determines the impact on the risk of increasing or reducing the requirements. These guidelines allow project managers and personnel to understand the issues involved in order to allow tradeoffs to be made. The failure modes generated for each requirement feed directly into the third task, Defect Detection and Prevention, which utilizes the Accurate, Cost-Effective Qualification (ACEQ) approach to systematically correlate these failure modes with the mission requirements. This process results in a matrix of weighted influence coefficients. When combined with a plot of failure modes versus the PACTS, a ranked list of PACTs is generated from which project personnel can tailor the qualification program for a particular mission. The forth task, Technology Readiness Assurance Guidelines, assesses the readiness of a new technology to be inserted into flight projects. This task provides the assurance status and need for infusion of new technologies into the Ncw Millennium Program.

NMP MISSION ASSURANCE PROJECT APPLICAITONS RTOP



3

Guidelines

1. Acoustic Noise Requirement

1.0 Objectives

Acoustic noise results from the propagation of sound pressure waves through air or other media. During the launch of a rocket, such noise is generated by the release of high velocity engine exhaust gases, by the resonant motion of internal engine components, and by the aerodynamic flow field associated with high speed vehicle movement through the atmosphere.

The fluctuating pressures associated with acoustic energy can cause vibration of structural components over a broad frequency band, ranging from about 20 Hz to 10,000 Hz and above. Such high frequency vibration can lead to rapid structural fatigue. Thus, the objective of a spacecraft acoustic noise requirement is to ensure structural integrity of the vehicle and its components in the vibroacoustic environment,

2.0 Typical Requirement

A typical acoustic noise requirement is illustrated in Figure 1 below

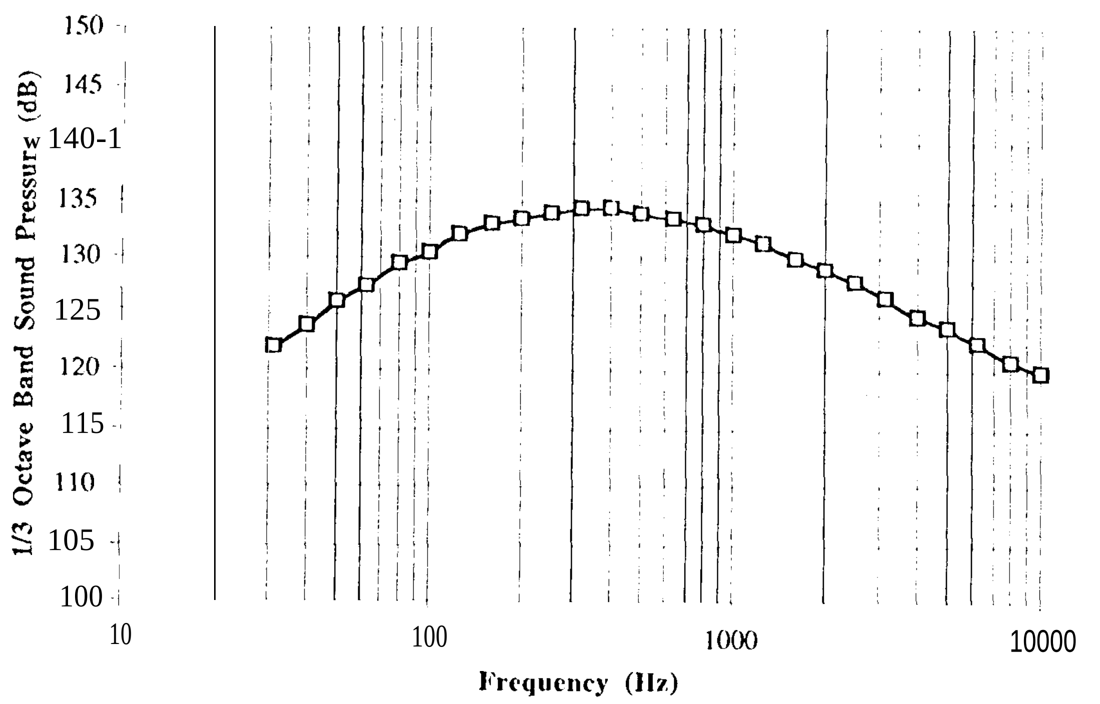


Figure 1 - Typical Acoustic Noise Requirement

Such a figure specifies the level of input sound pressure over the spectrum of frequencies at which the pressure can fluctuate. The pressure P is measured in decibels, defined as

$$dB = 20 \log \frac{P}{P_{ref}}$$

where the reference pressure $P_{ref} = 2 \times 10^{-5}$ Pa, ostensibly the audible limit of the human car.

The decibel pressure levels in acoustic noise.. spectra are not generally provided at each and every frequency. Instead, they are often specified over discreet bands of width Af, which span 1/S of a frequency octave. With this method, 3 sound pressure levels will be provided over any interval in which the frequency doubles. 'l'able 1 is an example of such a 1/S octave band specification, for the curve data-of Figure 1.

Table 1- Acoustic Specification	
Center Frequency	S1'1, (dB)
31.5	122.0
40.0	124.0
50.0	126.0
63.0	127.5
80.0	129.5
100.0	130.5
12s.0	132,0
I 60.0	133.0
200.0	133.5
250.0	134.0
315.0	134.5
400.0	134.5
500,0	134.0
630.0	133.5
803.0	133.0
1000,0	132.0
1250.0	131.5
1600.0	130.0
2000.0	129.0
2500.0	128.0
3150.0	126.5
4000.0	125.0
5000.0	124.0
6300.0	122.5
8000.0	121.0
10000.0	120.0

When pressure levels arc defined with these methods, it is convenient to provide a measure of the overal 1 acoustic noise intensity. The overall sound pressure level (OASPL) provides just such a measure and, for 1/3 octave band specifications, can be calculated as the decibel equivalent of the root sum square (RSS) pressure. Table 2 illustrates such a calculation for the. data of Table 1, and shows that the OASPL is 144.9 dB. It should be noted that this figure is greater than any individual sound pressure level in the specification, because it represents an intensity of the spectrum as a whole.

To quantify the acoustic environment, launch vehicles are often equipped with internal microphones, which measure noise levels within the rocket fairing. This telemetry data is relayed to the ground for processing, and ultimately plotted in the form of a sound pressure level versus frequency spectrum. Since the acoustic forcing function is stochastic, depending on many atmospheric and other variables, data from a number of such flights arc generally gathered, and an envelope, such as that of Figure 1, is developed to encompass the historical record of microphone data.

This process can be extended and applied to data from a number of launch vehicles. If a launch platform has not yet been manifested for a particular payload, acoustic profiles from a number of candidate rockets can be enveloped, producing an aggressive specification which will ensure design adequacy for the spacecraft, Figure 2 below reflects such a process, providing an envelope which encompasses the acoustic environments from three launch vehicles.

Table 2 - Calculation of Overall Sound Pressure Level

Center Frequency	SPL (all{})	Pressure P (Pa)	Squared Pressure
31.5	122,0	25.2	633.9
40.0	124.0	31.7	1004.6
50.0	126.0	39.9	1592.2
63.0	127..5	47.4	2249.1
80.0	129.S	59.7	3564,5
100.0	130.5	67.0	4487.5
125.0	132.0	79.6	6338.7
160.0	1 33.0	89.3	7979.9
200.0	133.5	94.6	8953.6
250.0	134.0	100,2	10046.?
315.0	134.5	106.2	11272.0
400.0	134.5	106.2	11272.0
500.0	134.0	1 00.2	10046.2
630.0	133.5	94.6	8953,6
800.0	133.0	89.3	7979.9
1000.0	132.0	79.6	6338.7
1250.0	131.5	75,2	5649.4
1600,0	I 30.0	63.2	3999.4
2000.0	129.0	56.4	3176.9
2500.0	128.0	50.2	2523.5
3150.0	126.S	423	1786.5
4000,0	12s.0	3S.6	1264.7
5000.0	124,0	31.7	1004.6
6300.0	122.5	26,7	711,2
8000.0	121.0	22.4	503.5
10000.0	120.0	20.0	399,9

RSS Pressure = 351.8 Pa

20 log(351.8/2E-5) = 144.9 dB

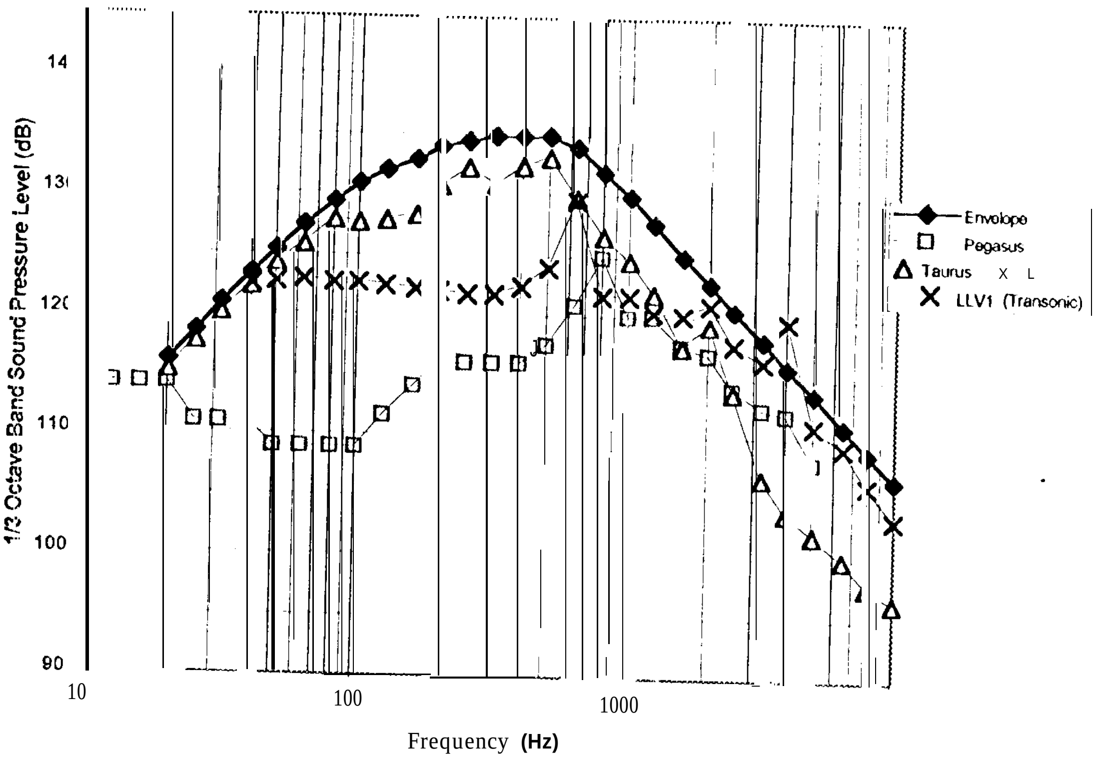


Figure 2 - Envelope of Acoustic Flight Data

2.1 Rationale

The rationale, for acoustic noise testing is straightforward, as acoustic energy is the primary source of vibration input to a space launch vehicle. During the initial phases of a rocket launch, high velocity gases arc ejected from motor nozzles and reflected from the ground, creating turbulence in the surrounding air and inducing a vibratory response of the rocket structure. During the subsequent ascent phase of a launch, as the vehicle accelerates through the atmosphere to high velocity, aerodynamic turbulence induces pressure fluctuations which again cause structural vibration. These pressure. fluctuations increase in severity as the vehicle approaches and passes through the speed of sound, due to the development and instability of local shock waves. The high-level acoustic noise environment continues during supersonic flight, generally until the maximum dynamic pressure or "max Q' condition is reached.

Acoustic energy gets transmitted to the mission payload in two ways. First, fluctuating pressures within the payload fairing impinge directly on exposed spacecraft surfaces, inducing vibration in high gain antennae, solar panels and other components having a large ratio of area-to-mass. Secondaril y, the fluctuating external pressure field causes an oscillatory response of the rocket structure, which is ultimately transmitted through the spacecraft attachment ring in the form of random vibration. From the spacecraft perspective, this random input is general] y lowest at the launch vehicle attachment plane, and increases upward along the payload axis.

At the integrated spacecraft level, then, acoustic noise is a primary source of vibration excitation. It is a "real world" environment, and should be included in virtually any space vehicle test program.

2.1.1 Failure Modes

The failure modes produced by acoustic noise excitation are generally identical to those associated with other types of vibratory structural fatigue. These include failures due (o excessive displacement, in which one deflecting component makes contact with another, as WC]] as fractured structural members and loose, fasteners. Broken solder joints, cracked PC boards and wave guides can also occur. Electronic components whose function depends on the motion of structural parts, such as relays and pressure switches, arc particularly susceptible.

Large flat panels arc most easily influenced by, and therefore damaged by, acoustic energy, as they can undergo large displacements whi le oscillating at low frequenc y. For a typical spacecraft, this means that a fixed high gain antenna must be carefully designed and stiffened to avoid bending failures, debonding of composite members and related problems. In general, any structure with a high ratio of surface area to mass can be expected to experience potential problems in the acoustic noise environment.

2.1.2 Supporting Data

Supporting data for acoustic noise design, analysis and testing can be found in the references listed below, as well as in various launch vehicle user manuals. At JPL the acoustic test has traditionally been severe, with the qualification environment generally established at 4dB above the expected launch noise profile. Table 3 provides a sampling of problems detected during acoustic tests on several major Laborat ory programs.

Table 3 - JPL Acoustic Test Problem/Failure History			
Program	**Year**	**Subsystem**	**Failure Mode**
Viking	1973	S/X Band Antenna	Cracked Epoxy
Viking	1973	SIX Band Antenna	Spacers Loosened
Viking	1973	SIX Band Antenna	Studs Loosened
Viking	1973	Infrared Mapper	Wire Shorted
Viking	1973	Radio Antenna	Screw Sheared
Voyager	1977	SIX Band Antenna	Magnetic Coil Debonded
Galileo	1983	Dust Detector	Sensor Cover Buckled
Mars Observer	1991	Telecom Subsystem	HGA Screws Backed Out
Mars Observer	1991	High Gain Antenna	HGA Struts Debonded
Mars Observer	1991	High Gain Antenna	Waveguide Broke
Topex	1992	Instrument Module	I/C Lead Wire Broke
Cassini	1995	High Gain Antenna	HGA Screws Backed Out
Cassini	1995	High Gain Antenna	HGA Struts Debonded

The testing has clearly identified improperly designed, underdesigned or undersized components. It is interesting to note that a majority of these problems have occurred in high gain antennas and related subsystems, which have the previously identified characteristics of large surface areas, low mass and bonded attachments.

3.0 Tradeoffs

Failure mode sensitivities and cost tradeoffs for the acoustic noise environment arc illustrated in Figure 3 below. The primary test variables arc acoustic noise input level, time duration for the test, frequency of noise input and whether or not power is on in the test article.
Each test parameter in an acoustic noise trial is generally a cost driver. This is primarily due to the fact that the test requires a large chamber, many support personnel and a significant amount of equipment.

Requirement	Control Parameters	Failure Mode	Sensitivity to Increase				Cost	
			dBpk	tdur	power	f		
Acoustic Noise	dB peak	intermittents	+	+	+	+	dB increase . more N?, etc	+
	t duration	broken solder joints	+	+	0	-	t duration change	+
	power on	opens	+	+	0	+	power 0" . extra equipt	+
	frequency	shorts	+	+	0	+		+
		broken connectors	+	+	0	-		
		broken waveguides	+	+	0	-		
		broken crystals	+	+	0	+		
		cracked diodes	+	+	0	+		
		relay chatter	+	+	+	+		
		fastener loosening	+	+	0	+		
		potentiometer slippage	+	+	0	+		

Figure 3 - Control Parameter Sensitivity and Cost

4.0 References

1. MIL-STD- 1540C, Test Requirements for Launch, Upper-Stage and Space Vehicles, United States Air Force Military Standard, 1994.
2. Steinberg, D. S., Vibration Analysis for Electronic Equipment, New York: John Wiley & Sons, 1986.
3. Himelblau, H., Fuller, C. and Scharton, T., "Assessment of Space Vehicle Aeroacoustic Vibration Prediction, Design and Testing," NASA CR-1596, July, 1970.

2. Pyrotechnic Shock Requirement

1.0 Objectives

Pyrotechnic Shock is a design and test condition under which flight hardware is subjected to a rapid transfer of energy. The energy transfer is associated with the firing of an explosive device, usually for the purpose of initiating or performing a mechanical action. Spacecraft separation events or the release of propulsion system safing devices are typical of such mechanical actions.

2.0 Typical Requirement

A typical pyrotechnic shock requirement is illustrated in Figure 1 below.

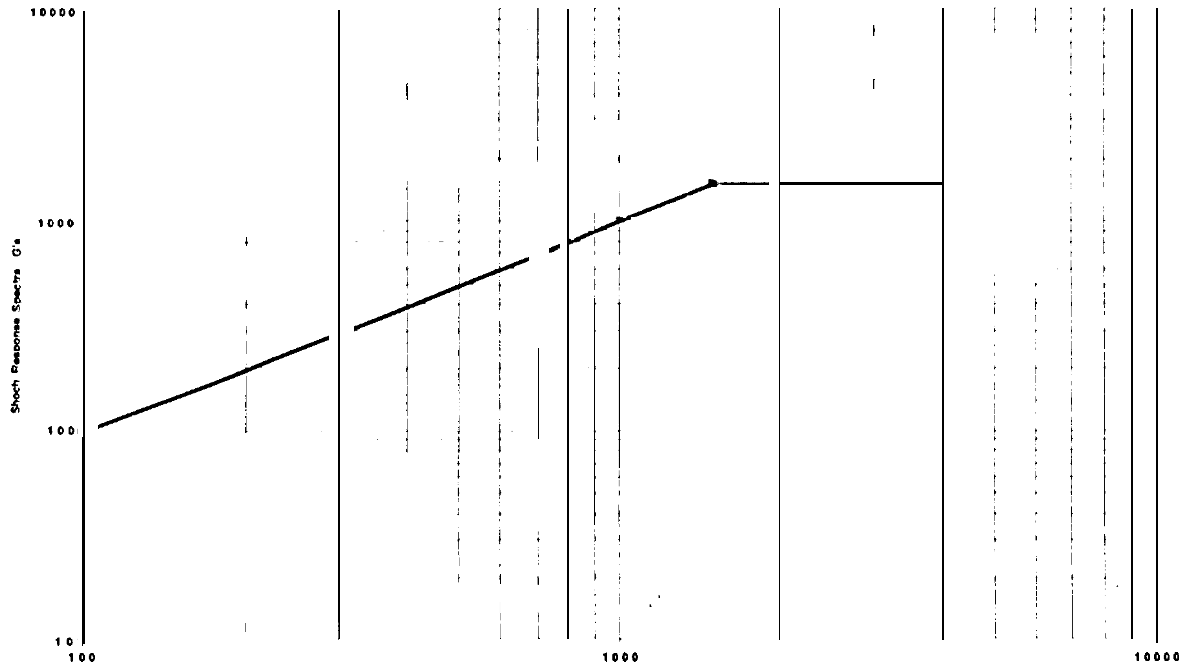


Figure 1 - Typical Pyrotechnic Shock Requirement

Such a figure gives the response of structure to the released shock energy, and illustrates a general trend that, as structural response frequency increases, the peak acceleration response increases as WC]].

2.1 Rationale

The release of energy from an ordnance-containing device and the subsequent transfer to surrounding structures represent a very complex event. As a result, it is difficult to describe the actual shape of the applied shock wave; it is generally not a simple time-based pulse such as a square or triangular wave. Figure 2 illustrates a typical acceleration versus time trace from an actual pyrotechnic shock event.